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Quarterly Technical Report - Report No. 4

October 1, 1992 - December 31, 1992

DARPA DICE Manufacturing Optimization

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Raytheon Company

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1. Summary

This is the Quarterly Technical Report for the DARPA DICE Manufacturing Optimization. The goal of the Manufacturing Optimization (MO) system is to facilitate a two tiered team approach to the product/process development cycle where the product design is analyzed by multiple manufacturing engineers, and the product/process changes are traded concurrently in the product and process domains. The system will support Design for Manufacturing and Assembly (DFMA) with a set of tools to model the manufacturing processes, and manage tradeoffs across multiple processes. The subject of this report is the technical work accomplished during the fourth quarter of the contract. This report describes highlights of the software design for the MO System, the results and presentation slides of the IPO/ISO presentation on "Supporting Concurrent Engineering and Information Exchange using STEP", and the slides presented at the DARPA ASEM Conference.

Raytheon completed and released the Software Design Specification for the MO System during this quarter. The specification contains the preliminary and detailed object oriented design, the user interface design, and the schema specifications for MO. The preliminary design discusses the capabilities and interfaces provided in the MO system. The detailed object oriented design describes the definition of the classes, objects, and methods which make up the MO system. The user interface design provides the look and feel of the system to the user, and the schema specification details the data behind the class and objects in the system.

Mr. Thomas Laliberty, Sr. Engineer, attended the joint meeting of the International Standards Organization (ISO) and the IGES/PDES Organization (IPO) in Dallas, TX on October 15-22, 1992. Tom presented an overview of the MO program and a walk-through of the PCB EXPRESS information models developed under the MO program. Mr. Laliberty also attended an EXPRESS users group meeting held in conjunction with the ISO/IPO meeting. A copy of the presentation is included in Appendix I of this report.

Mr. Robert Bryant, Program Manager, attended the DARPA sponsored ASEM Conference on October 28-30, 1992 in Arlington, VA. Robert gave a presentation on the Manufacturing Optimization program. A copy of the presentation is included in Appendix II of this report.

Raytheon will begin implementing the MO System during the next quarter based on the Software Design Specification for the Manufacturing Optimization (MO) System completed during the reporting period.

2. Introduction

This is the Quarterly Technical Report for the DARPA DICE Manufacturing Optimization. The concept behind the Manufacturing Optimization (MO) system is to facilitate a two tiered team approach to the product/process development cycle where the product design is analyzed by multiple manufacturing engineers, and the product/process changes are traded concurrently in the product and process domains. The system will support DFMA with a set of tools to model the manufacturing processes, and manage tradeoffs across multiple processes. The subject of this report is on the technical work accomplished during the fourth quarter of the contract. This report describes highlights of the software design for the MO System, and includes presentations given at the ISO/IPO meeting and the DARPA ASEM conference both held in October 1992.

Raytheon completed the Software Design Specification for the MO System. The specification contains the preliminary and detailed object oriented design, the user interface design, and the schema specifications for MO. The preliminary design discusses the capabilities and interfaces provided in the MO system. The detailed object oriented design describes the definition of the classes, objects, and methods which make up the MO system. The user interface design provides the look and feel of the system to the user, and the schema specification provides the details of the data behind the class and objects in the system. Section 3 contains a synopsis of the preliminary design section of the MO Software Design Specification. For more details refer to reference 5.

The ISO/IPO presentation was titled "Supporting Concurrent Engineering and Information Exchange using STEP". Section 4 contains a debriefing of the presentation and Appendix I contains the ISO/IPO presentation slides.

The ASEM presentation was titled "DARPA Initiative in Concurrent Engineering – Manufacturing Optimization (MO)". Appendix II contains the DARPA ASEM presentation slides.

3. MO Software Design

3.1 MO Overview

The concept of the Manufacturing Optimization (MO) system is to facilitate a two tiered team approach to the product/process development cycle where the product design is analyzed by multiple manufacturing engineers and the product/process changes are traded concurrently in the product and process domains. The system will support Design for Manufacturing and Assembly (DFMA) with a set of tools to model the manufacturing processes and manage tradeoffs across multiple processes. The lower level "specialized" team will transfer their suggested design changes back to the top-level product team as the Manufacturing Team's consolidated position.

The external software packages which the MO system is comprised of are the ROSE DB, Requirements Manager, and the Project Coordination Board/Communications Manager. For demonstration purposes, an interface was developed between Raytheon Automated Placement and Interconnect Design System (RAPIDS) and the ROSE DB. Figure 3.1-1 illustrates the external interfaces to the MO system.

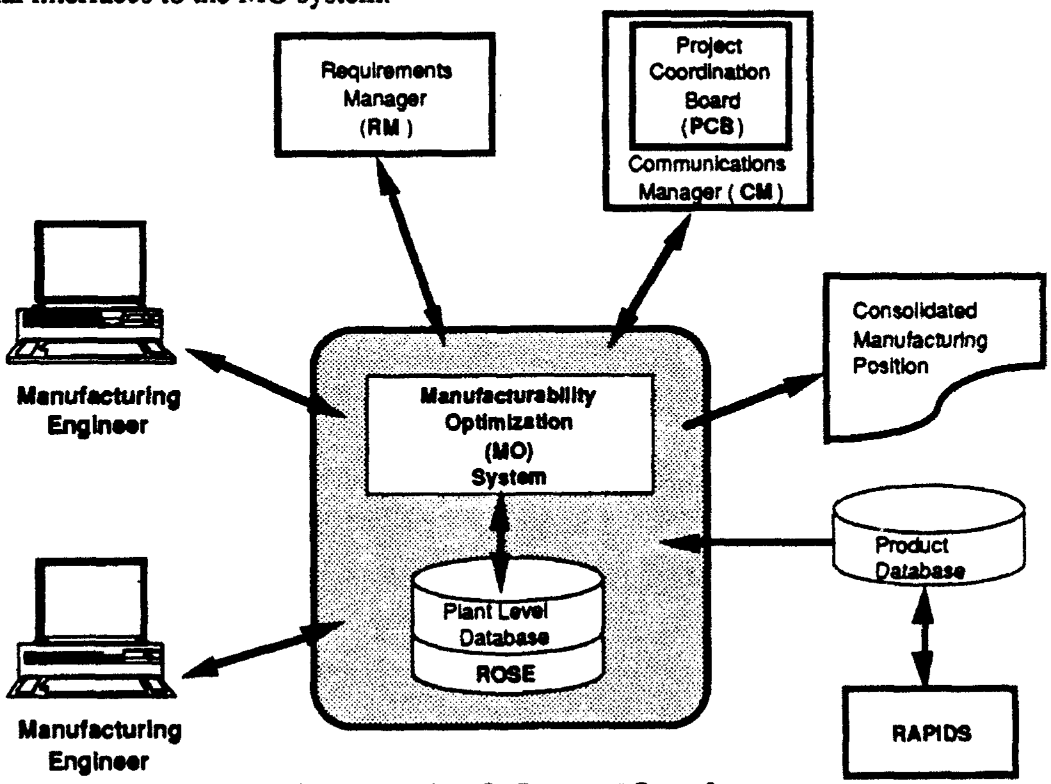

Figure 3.1-1 MO External Interfaces

ROSE is an object-oriented database management system that has been developed for engineering applications and enhanced to support the DICE program. ROSE is currently part of the STEP Programmer's Toolkit from STEP Tools, Inc. ROSE is a database which supports concurrency using a data model that allows the differences between two design versions to be computed as a delta file. The MO data for the manufacturing processes and operations, as well as, the various analysis results will be stored and managed within ROSE. The manufacturing process data consists of the process selection knowledge base, process and operation data, yield and rework data, and resource specifications.

The Requirements Manager (RM) is a software tool designed to manage product requirements and evaluate the compliance of product design data with requirements. The purpose of integrating the RM into the MO system is to provide the "top level" product development team insight into manufacturing requirements. It is common practice for a manufacturer to document manufacturability, or producibility guidelines which delineate standard manufacturing practices and acceptable design parameters. The purpose of these guidelines is to communicate the capabilities of the manufacturing process to the product design community to ensure that new product designs are specified within manufacturing capabilities. The guidelines delineate quantitative and qualitative producibility issues. The RM and the MO software will be tightly coupled through the RM's Application Programming Interface (API) to provide the user with a manufacturing guidelines analyzer capability.

The Project Coordination Board (PCB) provides support for the coordination of the product development activities in a cooperative environment. It provides common visibility and change notifications. The Communications Manager (CM) is a collection of modules that facilitates distributed computing in a heterogeneous network. The Communication and Directory Services provided in the CM module are required to utilize the PCB. The PCB/CM will be used in MO to support the communication of the product/process development activities. There will be no direct interface between the MO software modules and the PCB/CM applications. It will be used to manage the product task structure.

RAPIDS is Raytheon's conceptual design and analysis workstation for Printed Wiring Boards (PWB). RAPIDS supports component placement and placement density analysis, as well as a number of other analysis functions, including automatic component insertion checking and thermal analysis.

3.2 MO Architecture

MO is a X-Windows based tool. The application software will be written in C++, the user interface will be developed using OSF/Motif Widgets, and all data will be stored in STEP physical files.

The decision to use STEP physical files for the underlying data format for the MO system stems from the fact that STEP is the emerging international standard for data exchange between automation systems. Access to these STEP files will be provided through the STEP Programmer's Toolkit from STEP Tools Inc. The Toolkit provides a means of reading and writing STEP entity instances through a C++ class library.

The MO core system is composed of three software modules, Manufacturing Analyzer, Manufacturing Advisor, and Process Modeler. The Project Coordination Board (PCB) and Communications Manager (CM) from Concurrent Engineering Research Center (CERC), ProductTrack Requirements Manager (RM) from Cimflex Teknowledge, the ROSE database from STEP Tools Inc., and the two way interface to the Raytheon Automated Placement and Interconnect Design System (RAPIDS) complete the software suite which constitute the MO system. Figure 3.2-1 illustrates the MO System Architecture.

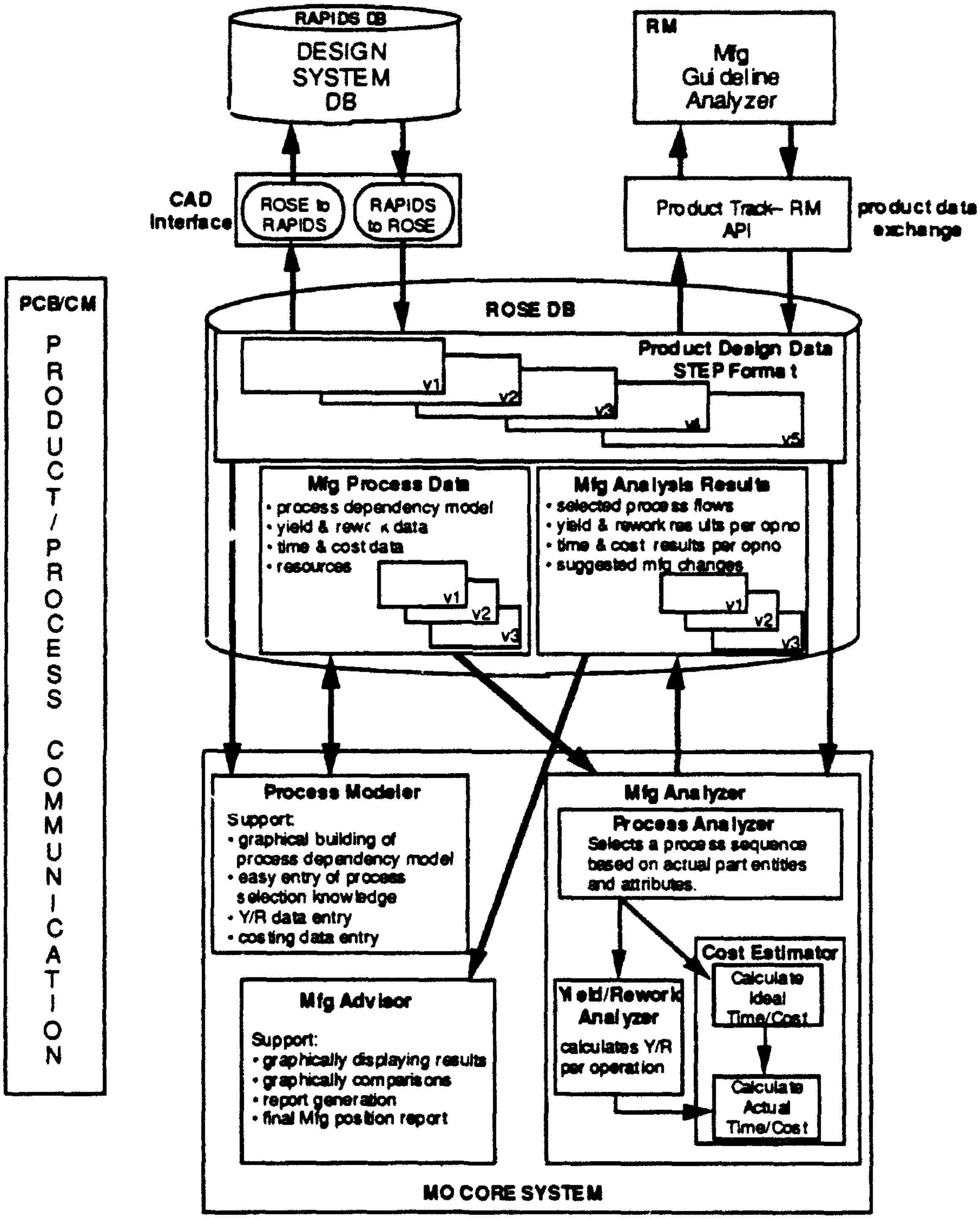

Figure 3.2-1 MO System Architecture

The Process Modeler provides the user with the ability to model processes required to manufacture a product. Each process is modeled as a set of operations, where an operation is a unit of work performed on the product part. Resources, yield rates, and rework rates are defined for each operation. The output of the Process Modeler is a directed acyclic dependency graph of individual manufacturing processes. Figure 3.2-2 depicts a block diagram of the Process Modeler.

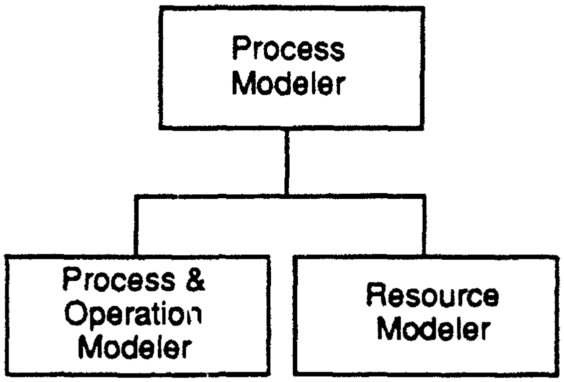

Figure 3.2-2 Process Modeler Block Diagram

Figure 3.2-3 illustrates a simplified subset of a process model. The example models the processes required to etch conductive material from a printed wiring board substrate.

The process modeler provides the ability to establish dependencies between processes. In the example, the "Etch Material" process is dependent on the "Etch FLEX" process OR the "Etch Substrate" process. Note that if the AND/OR flag of the "Etch Material" process were set to AND, then the "Etch Material" process would be dependent on both of its parents processes. Attached to the "Etch Material" process is a list of selection rules which provide the reason(s) why this process would be relevant, and a list of operations which must be performed to complete the etch material process. Defined with each operation are scrap rates, rework rates, setup time, run time, and a list of resources required to complete the operation.

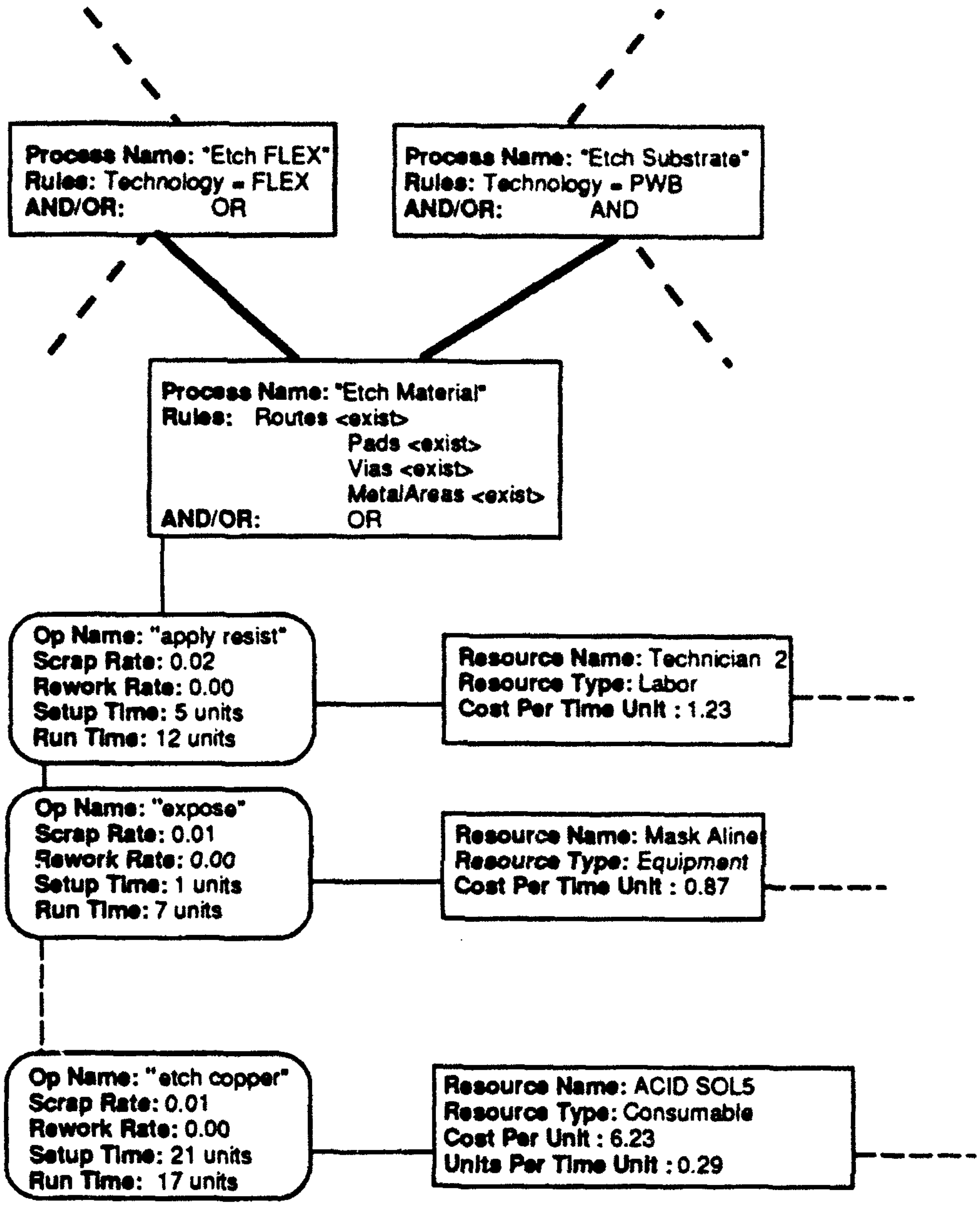

Figure 3.2-3 Example subset process model for etching process

The Manufacturing Analyzer provides the following three services: 1. Select the individual processes from the process model that are used to manufacture a particular product. 2 Analyze the processes selected and the operations attached to each process to estimate scrap and rework rates. 3. Analyze the resources needed to perform the operations attached to the selected processes for cost. The analyzer results are composed of design feature entities from the product design database (STEP file) along with the selected manufacturing processes from the user specified process model. Figure 3.2-4 depicts a functional block diagram of the Manufacturing Analyzer.

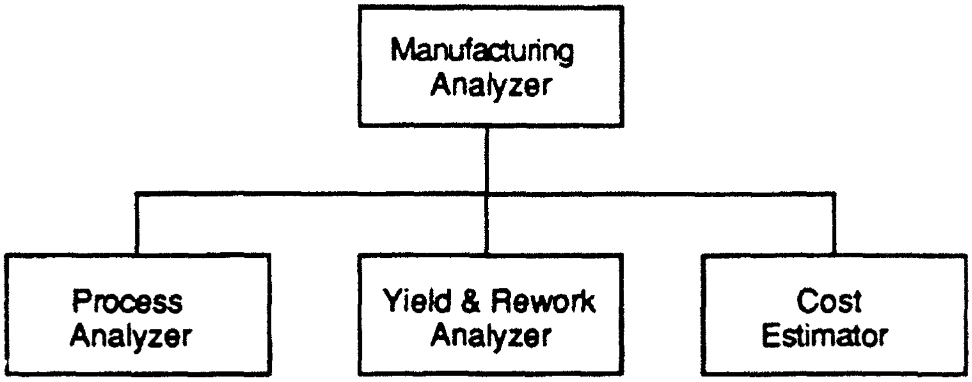

Figure 3.2-4 Manufacturing Analyzer Block Diagram

To illustrate all the Analyzer functionality (i.e. analysis of manufacturing process, yield, rework, and cost), lets utilize the example process model for the etch process defined in Figure 3.2-3. Lets walk through the steps that the process analyzer, yield/rework analyzer, and cost estimator will go through for determining selection of the "Etch Material" process. Consider that the product design data under analysis contains the following: an entity called Technology with a value of "PWB" and several Route, Pad, and Via entities.

To determine if the "Etch Material" process should be selected, the Process Analyzer will first determine if either of its parent nodes were previously selected as applicable processes. Since the product data contains a Technology entity set to PWB, the selection rules of the "Etch Substrate" process would have been satisfied; therefore, the process would have been previously selected. Since the AND/OR flag of the "Etch Material" process is set to OR only one of its parents must be selected before the Process Analyzer will evaluate its process selection rules. Since the product data set contains several routes, pads, and vias, the selection rules evaluate to true, thereby, satisfying all the process selection criteria. At that point, the process analyzer would add the "Etch Material" process to the resulting analysis flow along with the associated design feature entities from the product design.

Once the "Etch Material" process is selected, the Yield/Rework Analyzer will evaluate each operation attached to it to estimate scrap and rework rates associated with this particular product. Finally, the cost estimator will calculate the cost associated with the resources attached to each of the operations.

The Manufacturing Advisor provides the user with various methods to view the results produced from the analyzer. The results can be viewed graphically (i.e. line, bar, stacked bar and pie charts) or textually. The reporting capability allows the user to customize a detailed report which can be printed to the screen or to an ASCII file. MO allows the user to view one or more sets of analysis results at a time. By selecting multiple analysis runs to graphically display, the user can visually compare the analyses. Figure 3.2-5 shows a functional block diagram of the Manufacturing Advisor.

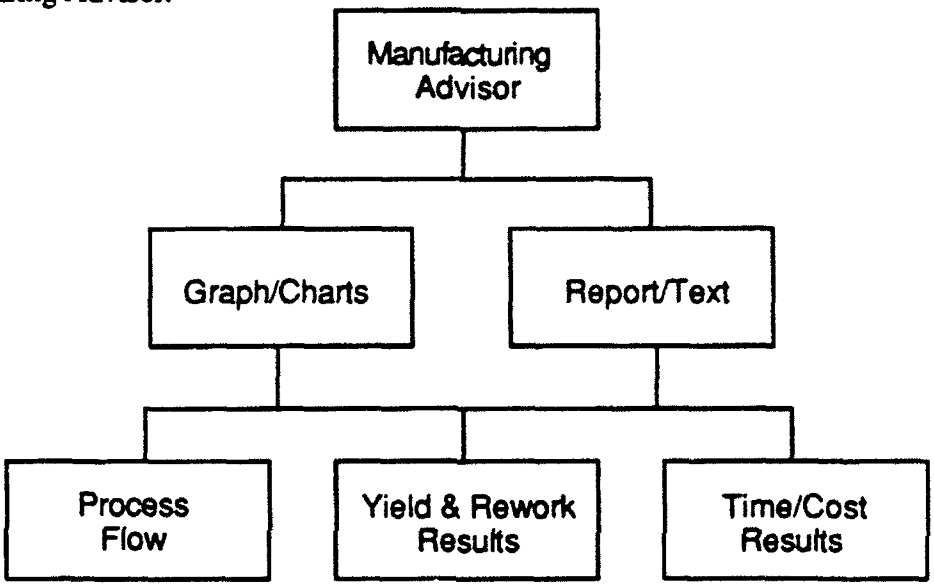

Figure 3.2-5 Manufacturing Advisor Block Diagram

The interaction between the user, manufacturing analyzer, process modeler, manufacturing advisor, RM, PCB/CM, RAPIDS, and ROSE DB is pictured in Figure 3.2-6.

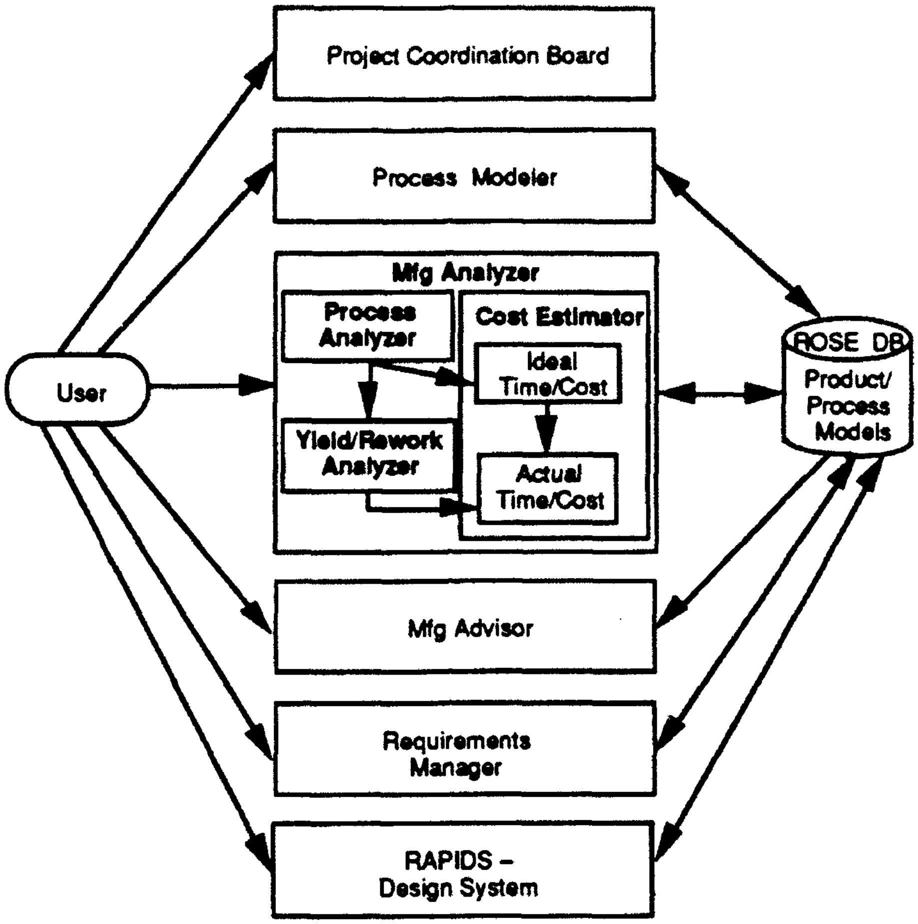

Figure 3.2-6 MO Data Flow

3.3 MO Design Description

3.3.1 External Interfaces

3.3.1.1 Project Coordination Board

The Project Coordination Board (PCB) is a system developed to provide support for the coordination of the product development activities in a cooperative environment. The PCB provides common visibility and change notification through the common workspace, planning and scheduling of activities through the task structure, monitoring progress of product development through the product structure (i.e. constraints), and computer support for team structure through messages. The Communications Manager (CM) is a collection of modules that facilitates distributed computing in a heterogeneous network. It promotes the notion of a virtual network of resources which the project team members can exploit without any prior knowledge of the underlying physical network. The Communication and Directory Services provided in the CM module are required to utilize the PCB.

MO introduces the concept of a two tiered virtual tiger team. The two tiered approach consists of a cross functional product team linked to teams within each of the functions, in this case a manufacturing process team. To implement this approach there must be communication among the members of each team, and between the product and process team. The PCB/CM is being used to support the following capabilities which are required for this type of communication:

- Product - to - Process Team Communication
    - Notification of design task completed.
    - Notification and issuance of database available for analysis.
    - Notification of alternative designs or trade-off decisions under consideration.
- Process - to - Product Team Communication
    - Notification and issuance of analysis results.
    - Notification and issuance of modified database with recommended changes.
    - Notification of changes to the process, guidelines, cost or yield models.

We are using the product task structure within the PCB/CM to model the product to process development team communication. Included in this task structure are major design steps, such as concept development, design capture, design verification, component placement, routing, transition to production, and several design reviews. The design reviews included representatives from design, test, reliability, manufacturing, and thermal. Figure 3.3-1 is a high level view which represents the design cycle steps which model a typical PWB product design cycle.

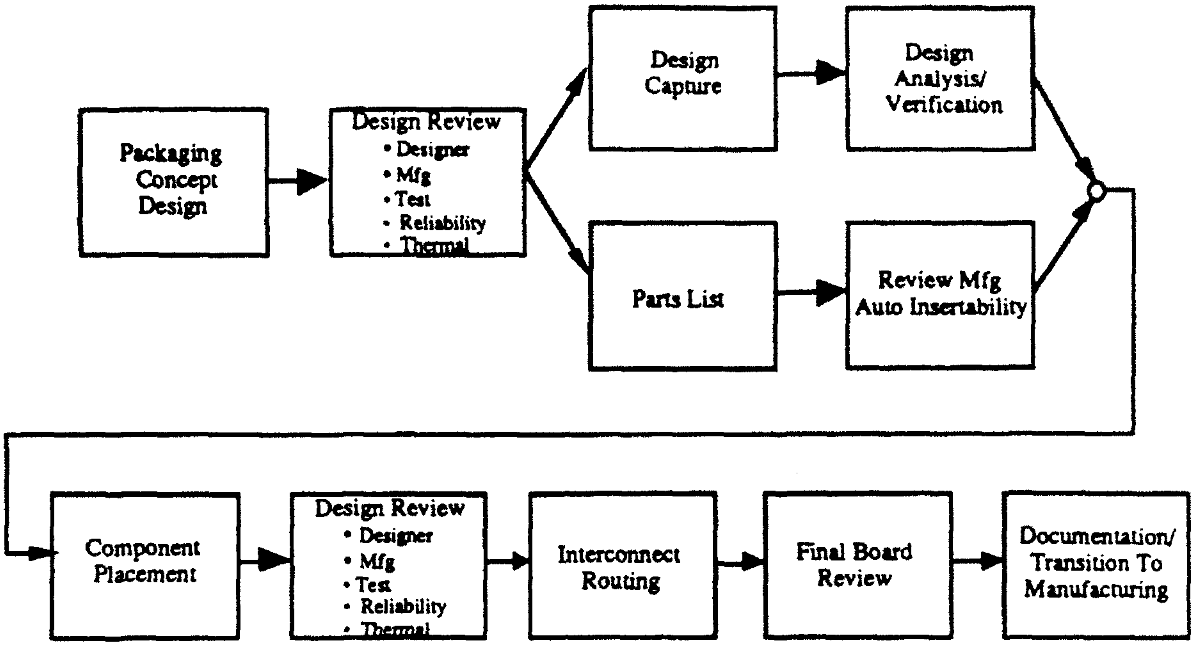

Figure 3.3-1 Sample PWB Design Cycle Flow

The Project Lead (user with special privileges) initializes the product task structure. The Project Lead can then view any task or work order that appears in the network, add a task to the existing network, acknowledge receiving a task, and indicate completion of a task. The other team members can acknowledge receiving a task and indicate completion of that task. The PCB automatically dispatches tasks as previous tasks are completed, as well as, the Project Lead can dispatch a task. Refer to reference 15 for details on the PCB.

3.3.1.2 Requirements Manager

The Requirements Manager (RM) is a software tool designed to manage product requirements and evaluate the compliance of product design data with requirements. The tool allows the user to model requirements or guidelines, model the product design data structure, populate the product design data structure with product data, and evaluate to what extent the product design data meets the specified requirements. As a result of the evaluation process, the tool will provide the user with a status (Pass, Fail, Uncertain, or Untested) of the compliance of the product data with the requirements. The MO manufacturing guideline functionality is being incorporated into the RM to provide the "top level" product development team insight into manufacturing requirements apart from the MO analyses.

It is common practice for a manufacturer to document manufacturability, or producibility guidelines that delineate standard manufacturing practices and acceptable design parameters. The purpose of these guidelines is to communicate the capabilities of the manufacturing process to the product design community to ensure that new product designs are specified within manufacturing capabilities. The guidelines delineate quantitative and qualitative producibility issues.

The MO system is supporting evaluation of these manufacturing guidelines. For each guideline entry there is a related recommendation. Unlike the process selection constraints, manufacturability guideline violations may not cause alternative selection. The result could be an operation cost increase, for instance, the need for non-standard tooling, a yield loss, or a less tangible impact. These guidelines will be entered into the Requirements Manager so that they are available to the product design team along with the other requirements placed on the design. Some examples of these guidelines include: "The maximum board dimension must be less than 14 inches", "Switches must be hermetically sealed", or "If the number of leads is less than or equal to 24 the span should be 0.3 inches". See reference 10 for details on the RM.

3.3.1.3 RAPIDS

RAPIDS is Raytheon's conceptual design and analysis workstation for Printed Wiring Boards (PWB). RAPIDS supports component placement and placement density analysis, as well as a number of other analysis functions, including automatic component insertion checking. Interfaces between RAPIDS and the PWB analysis tools for the following criteria are also provided as part of the RAPIDS tool suite:

- Manufacturing
- Post Layout Effects
- Reliability
- Thermal

At Raytheon, RAPIDS is used for conceptual design and analysis of PWB's. RAPIDS serves in the same capacity at Raytheon that many commercial CAD systems (e.g. Mentor Board Station, Racal-Redac Visula, Cadence, etc.) are used in at other companies. RAPIDS provides an Application Programmatic Interface (API) with its database. This enables RAPIDS to be easily interfaced with other systems and standards. Using RAPIDS in the MO system is inline with Raytheon methodologies, but does not exclude interfacing MO with commercially available CAD systems in the future. The key to interfacing MO with a large base of CAD systems is the utilization of the STEP standard by the commercial CAD industry. See reference 11 for details on the RAPIDS Data Dictionary.

3.3.2 Product (STEP) Models

All data required for the MO system will be stored in STEP physical files. The reason behind the use of STEP physical files is that STEP is an emerging international standard which is getting wide spread attention as the means of exchanging data between automation systems. Access to the STEP files will be provided through the STEP Toolkit (STEP Tools Inc.). The Toolkit provides a means of reading and writing STEP entity instances through a C++ class library. This class library is currently being updated to adhere to the ISO Part 22 SDAI (Standard Data Access Interface) specification.

At Raytheon, PWB product data is stored in the RAPIDS (Raytheon's Automated Placement and Interconnect Design System) database. Two interfaces were developed to support the transition of PWB product data to and from STEP physical files.

Generating the STEP physical file is facilitated by the *RAPIDS to STEP* interface which maps RAPIDS data items into instantiated STEP entities. An information model using the EXPRESS information modeling language was created based on the RAPIDS database. The EXPRESS information model was compiled using the STEP Tools *express2c++* compiler, which generated a STEP schema and a C++ class library. The class library consists of methods for creating and referencing persistent instances of the STEP entities which are stored in a ROSE database. The STEP schema is used by the STEP Tools *STEP filer* for reading and writing the STEP physical file.

The MO system uses the STEP data directly, as well as, for information exchange between the members of the product design team. For demonstration purposes, we will have the top level team using RAPIDS. This is not a requirement for using the MO system. The only requirement is that the top level team and the lower level teams be capable of creating, exchanging and using the STEP physical file.

The Manufacturing Team passes back a consolidated manufacturing position to the product design team. To aid in the generation of a consolidated position, conflict resolution and design merging must be supported. This is done using the STEP Toolkit from STEP Tools Inc. The *diff* tool reads two versions of a design and creates a delta file. The *difference report generator* reads the difference file and the original design, and presents each STEP entity and its attributes with the original values and its change state clearly marked with an asterisks.

Once the conflicts of the Manufacturing team members have been resolved, design versions are merged using the STEP Tools *sed* tool. The *sed* tool reads the delta file created by the *diff* tool and updates the original design version. This updated version of the design will be transferred back to the top-level product team as the Manufacturing Team's consolidated position.

3.3.3 Process Models

The key to performing manufacturability analysis is to characterize the fabrication and assembly processes. In MO, this characterization is implemented as a manufacturing process representation and selection algorithm. Basing manufacturing cost analysis on a detailed description of the process provides visibility into the relationshi between the design attributes and the manufacturing process. This allows the engineer to focus on manufacturing cost drivers and their causes. By characterizing the process *in this manner*, the manufacturing engineer will be able to review the process which will be used to produce the product and be readily able to consider alternative manufacturing processes and their consequences.

Following this logic, it makes sense to capture the expert's process planning knowledge into a process selection model so that the relationship between the product entities and the process selected to fabricate the product is explicitly defined. This does not mean that there is a one to one relationship between the design entities and the process steps. In some areas, such as PWB, the design may be implemented using different technologies, each of which implies a certain process, such as surface mount versus through-hole technology. In other cases, there are multiple processes that can be used to produce the same entity. This is most prevalent in the metal fabrication (machining) area where often a number of processes (investment casting, milling) are capable of producing the part.

There are two development challenges: building a data schema to represent the manufacturing process such that it can be used for selection and costing, and building a selection logic algorithm that adequately represents the planning logic employed by expert process planning.

Normally in a manufacturing plant, the overall process for a given discipline is known and recorded in the form of a flowchart. This flowchart is a block diagram listing of each and every process within that discipline. The order of those operations is structured so that it is the default ordering of how products flow. If a process gets repeated, it generally shows up in each repeated point in the flow chart. These flowcharts usually employ a rudimentary decision logic scheme. As such it represents the available processes in a pick list fashion. Pictured in figure 3.3-2 is a typical manufacturing process flow for printed wiring boards.

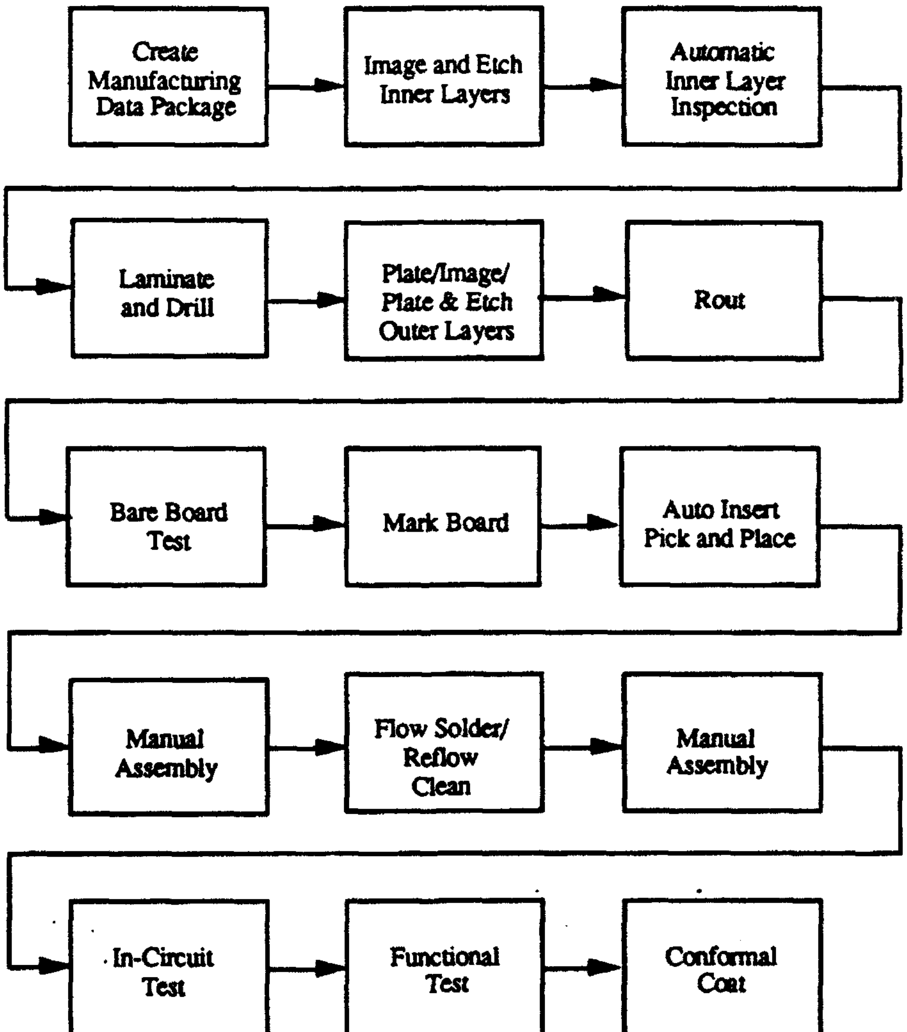

Figure 3.3-2 Printed Wiring Board Manufacturing Flow

The logic representation method that Raytheon is developing for this task is based on prior work in process selection. The model is a hybrid and/or dependency graph and rule based processing system. The and/or dependency graph representation was selected because it allows the system to display the basic sequential and concurrent flow of the process in a presentation format where the manufacturing engineer can visually see other process(es) that a selected process is dependent on. The dependencies inform the user of the basic flow of the overall process while letting the user plan at various levels of abstraction. These levels include the process, an organized group of manufacturing operations sharing characteristics, the operation, a common unit of work that is performed on the part, and the resource, which is the mechanism required to perform the operation. By defining the levels as we have, a hierarchical planning strategy is enabled. Using this schema, we can reason about alternative processes, plan the operation flow within the selected process, and then detail the individual resources of that operation, such as set-up and run time standards.

The reasoning process is guided by the representation of the dependency graph which sets the initial search evaluation order, and the rule processing mechanisms. The rules are attached to individual process nodes in the graph. These rules are used to evaluate the node. The purpose of the evaluation is to cause selection of the node. First, any parent processes that the process under evaluation is dependent on must be satisfied. If satisfied, the rules attached to the process are evaluated to see if it is applicable to manufacturing the product part. Operations are stored to form the overall manufacturing process sequence. Each operation in the process sequence is evaluated for its requirement of resources in order to estimate the manufacturing process cost.

The system will also have the ability to store alternative models of a particular process. This capability will allow the process engineer the ability to explore alternative process approaches and plan process improvements. Figure 3.3-3 illustrates a sample assembly dependency graph for through-hole circuit cards.

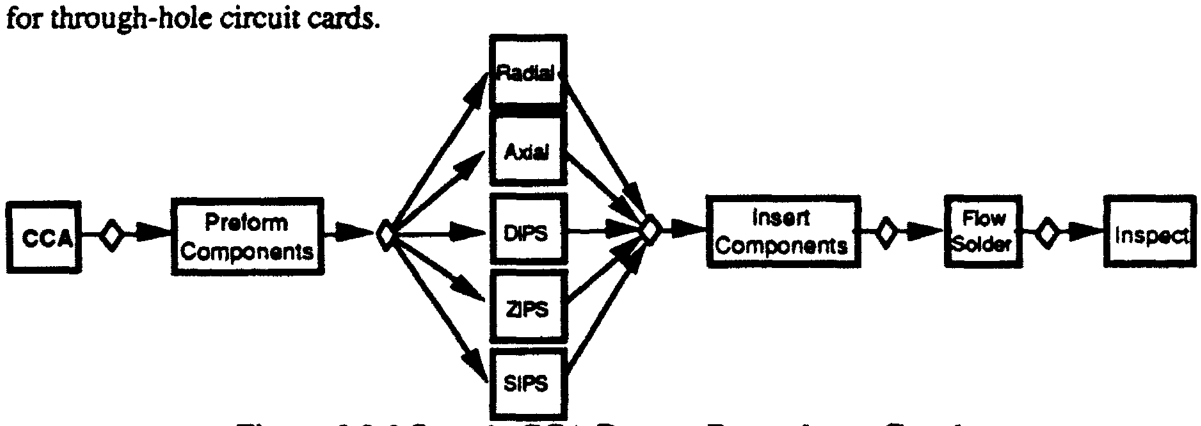

Figure 3.3-3 Sample CCA Process Dependency Graph

3.3.4 Manufacturing Analyzer

There are three capabilities provided in the Manufacturing Analyzer module: process analyzer, yield and rework analyzer, and cost estimator. The sub-sections to follow describe each capability.

3.3.4.1 Process Analyzer

The Process Analyzer provides the capability to select or determine the process sequence required to manufacture the product design based on a particular process model. The manufacturing process is represented by three levels of abstractions: process, operation and resource. The process is an organized group of manufacturing operations, the operation is a common unit of work that is performed on the part, and the resource is the mechanism required to perform the operation. The process model for the MO system is designed as an "and/or dependency graph" made up of selectable manufacturing processes. Each process node in the graph can be connected to process(es) at a higher level and/or lower level in the graph. A list of applicable operations and resources can be attached to the process in the dependency graph. Each operation has applicable yield and rework rates attached. Refer to reference 5 Section 6.1 for the details of the process model schema.

The Analyzer will select the applicable process(es) on a level by level basis using the selected process model. First, the and/or prerequisite of the parent(s) of the process must be satisfied. If satisfied, the rules attached to the process are evaluated to see if it is an applicable process. The selected process and corresponding product design entities will be added to a dependency analysis graph. Figure 3.3-4 illustrates a resulting high level process analysis graph for a circuit card.

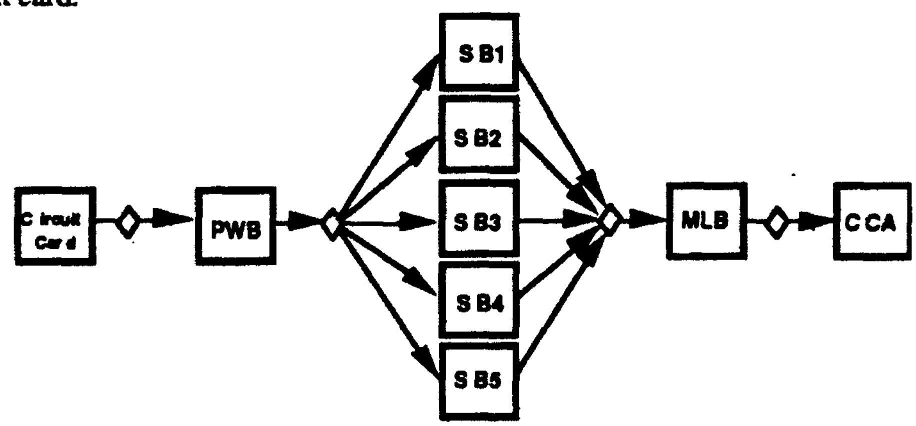

Figure 3.3-4 High Level Process Analysis Graph

3.3.4.2 Yield & Rework Analyzer

The yield and rework analyzer provides the capability to calculate yield and rework rates for the selected processes associated with a product design. This part of the analysis calculates the yield and/or rework rate on an operation level within the process. The rate will be calculated based on the design entities influence on the operation. The yield and/or rework rate for each design entity/entities associated with an operation is calculated through the evaluation of a rule, which has a corresponding equation attached. If the rule evaluates to true, then the equation will be calculated to provide the yield or rework rate. The rate equations may include references to the existence, value, or quantity of product design entities. An example yield rule and corresponding rate attached to an operation is as follows:

Yield Data:

Design Features Rule	Scrap Rate
aspect ratio < 5.0 & aspect ratio > 4.0	0.05000
aspect ratio <= 4.0 & aspect ratio > 2.0	0.02000

The total yield rate for an operation is calculated using the statistical probability of each design entity scrap rate to each other by calculating the independent events. The total rework rate for an operation is calculated by summing up the results of each rework occurrence.

3.3.4.3 Cost Estimator

The cost estimator calculates the recurring manufacturing cost for each operation in the process sequence. The following calculations are performed:

- Labor standards for each resource attached to an operation are calculated for setup and run time utilization. The value for each is calculated through the evaluation of an equation which may include reference to the existence, value, or quantity of design entities in the product data. Each resource has an associated cost in terms of an appropriate measure. For example, a labor resource will have an associated cost in terms of dollars per time unit.
- Estimated ideal cost for each operation is calculated from labor standard values multiplied by the wage rate of the labor grade or bid code of the resource(s) performing the operation, and the production efficiency value for that operation.
- Rework operations are calculated based on the rework rate determined by the yield and rework analyzer multiplied by labor standards of the resources for the rework condition. The labor grade wage rates and production efficiencies would then be applied.
- For each operation, the estimated actual cost is calculated by multiplying the estimated ideal cost by the number of units processed, including both good and scrapped units. The number of units processed by each operation are calculated from the value of the required good units at the subsequent operation divided by the yield at the operation under

evaluation. For example, if the desired production quantity is 100 boards and operation 1 has a scrap rate of 5%, then the quantity of units required for operation 1 would be 105.

- The total estimated ideal cost and total estimated actual cost for each sequence of processes are calculated by summing the individual operation cost of each process. The estimated actual cost for a good unit is calculated by dividing the total estimated actual cost for the process by the number of good units produced.

3.3.5 Manufacturing Advisor

The manufacturing advisor provides the capability to view the results produced by each process participating in an analysis. The advisor includes the following capabilities:

- A mechanism for selecting one or more manufacturing analyzer runs for comparing and/or displaying the results.
- Graphical capabilities (i.e. line, bar, stacked bar and pie charts) for comparing and displaying the process, yield, rework, or cost versus a processes or operations for one or more manufacturing analyzer runs.
- A reporting capability which prints analyzer results to the screen or file for one or more runs including process sequence, yield and rework, and cost.
- The capability to summarize design entities causing manufacturing guideline violations (interface to the RM) across multiple processes. Report recommendations on these guideline violations.
- A final manufacturing summary report, identifying cost drivers, for each process contributing to a multi-process analysis for a given design database after completion of the manufacturing optimization process.

Provided below in figure 3.3-5 is a sample of the type of graphical display the user would see for yield versus process.

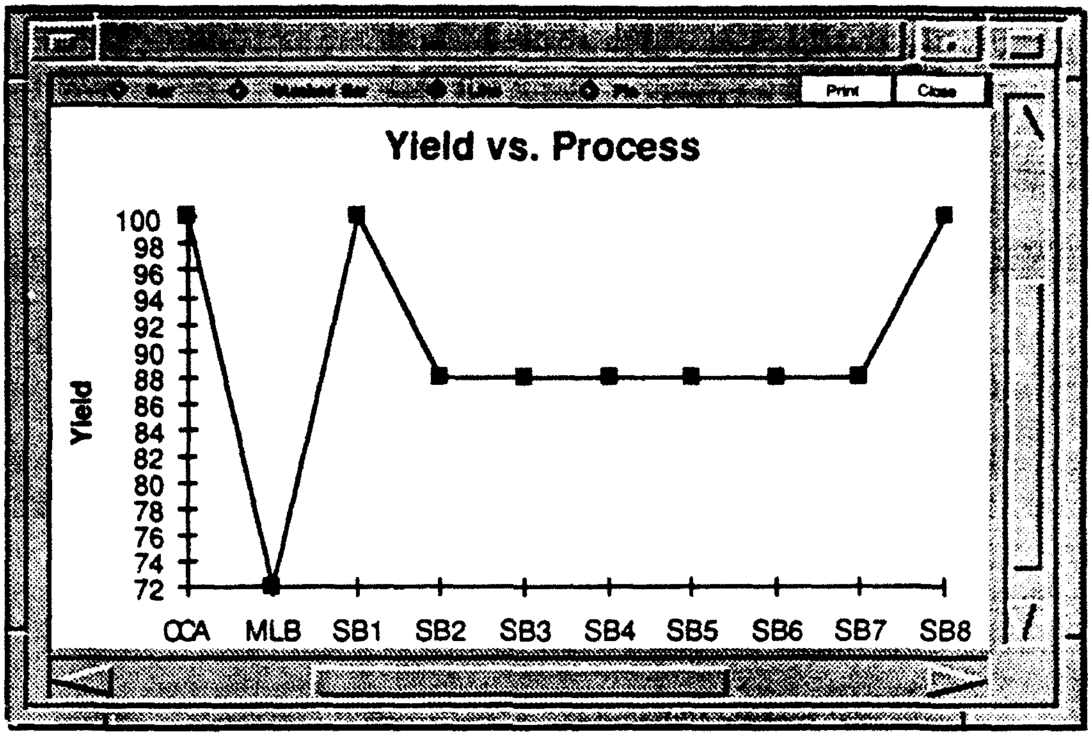

Figure 3.3-5 Sample Yield versus Process Display Graph

3.3.6 Process Modeler

The process modeler provides the capability to model the selection logic of the manufacturing process. The process model is decomposed into a graph of process nodes. Each process node consists of the following:

- Selection rules - If these rules are satisfied and this node's dependencies are satisfied, then the process node is included in the total process analysis model.
- Dependencies (parent process nodes) - For the node under consideration to be selected, all of the process nodes that it is dependent on must be satisfied. An AND/OR flag is stored as each node in the graph. If the flag is set to AND then, the node is dependent on all of its parents. If the flag is set to OR, then the node is depending on only one of its parents to be satisfied.
- Operations - At each process node there is a list of operations that are performed. Each operation is annotated with an associated yield rate, rework rate, and its usage of resources.
- Resources - At each process and operation node there is a list of resources attached. A resource is any facility, person, equipment, or consumable material used in the manufacturing process.

The MO system will allow the manufacturing specialists to capture and maintain multiple copies of process data models through a set of utilities. The utilities will provide the model developer with the tools necessary to graphically build and view the process logic dependency graph, selection rules, yield/rework, labor standards, and resources. Through the use of these utilities, the process team will have the ability to modify the process model data, to explore alternative process approaches and plan process improvements, and then analyze the effects of these changes on the product cost. The user interface will consist of pull down menus and pop up forms to allow adding, copying, moving, deleting, editing, and printing of the processes in the dependency graph. Pictured below in figure 3.3-6 is the main user interface window for the Process Modeler with a sample process model displayed.

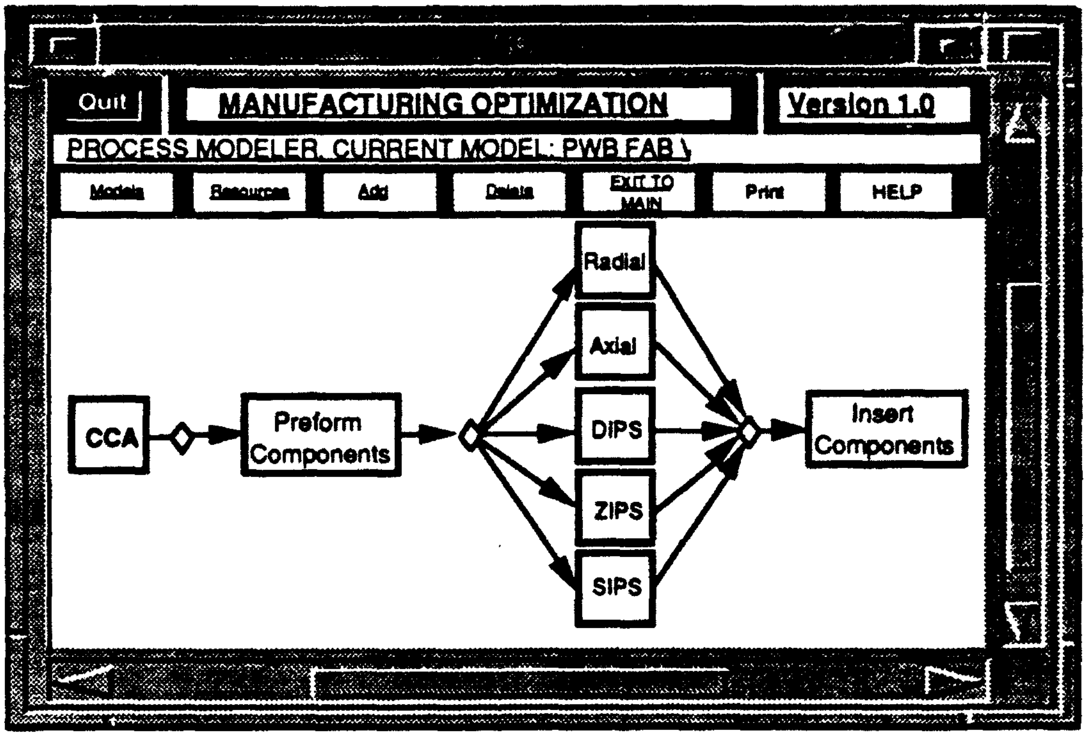

Figure 3.3-6 Process Modeler User Interface Window

4. IPO/ISO Presentation

Mr. Thomas Laliberty attended the joint meeting of the International Standards Organization (ISO) and the IGES / PDES Organization (IPO) in Dallas, TX held October 15–22, 1992. The purpose of the trip was to present the Printed Circuit Board (PCB) EXPRESS Information models and interface of the DICE MO program to the ISO/IPO standards body. The material was presented to the Electrical/Electronic/Electrotechnical joint working group (JWG9, commonly referred to as E*).

The scope of JWG9 is to develop application resource models (STEP 100 series parts) and Application Protocols (AP's, 200 series parts) for electrical, and electronic products and the technical documentation accompanying them. This is to be done using STEP methodologies taking into account documented efforts such as EDIF, IGES, SET, VHDL, and VDN. Currently the following three AP's and two application resource models are under development and fall under the scope of E*:

- Part 210, AP "PCA (Printed Circuit Assembly): Design and Manufacturing"
- Part 211, AP "PCA: Diagnostics, Test, and Remanufacture"
- Part 212, AP "Electrotechnical Plants"
- Part 103, "Electrical Connectivity"
- Part 1xx, "Diagrams used in Electrotechnology" *(number not assigned yet)*

A detailed overview of the work done on each of the Parts listed above was presented. Parts 210, 212, 103, and 1xx are being developed by PDES Inc. Part 211 (AP PCA: Diagnostics, Test, and Remanufacture) is being developed under the PAP-E (PDES Application Protocol - Electronics) program. Raytheon is a PAP-E subcontractor.

The presentation of the DICE MO program work was well received. Material presented included the following :

- MO program history
- MO program goals and concepts
- MO prototype system
    - RAPIDS
    - MOSS
    - STEP Tools
    - CERC Tools
    - MO Architecture
- Future Plans
- PWB EXPRESS models

At the conclusion of the presentation, Jack Corley, the PDES Inc. Electrical Project Manager expressed an interest in working with the MO program. He is responsible for Part 210, AP PCA (Printed Circuit Assembly): Design and Manufacturing. The PDES Inc. Electrical Project would like to review the PWB EXPRESS models developed under the MO program to ensure that Part 210 has coverage of the data modeled in the MO PWB model. The presentation slides are located in Appendix I.

5. Conclusions

During this reporting period, the MO Software Design Specification was completed. The specification contains the preliminary and detailed object oriented design, the user interface design, and the schema specifications for MO. The preliminary design discusses the capabilities and interfaces provided in the MO system. The detailed object oriented design describes the definition of the classes, objects, and methods which make up the MO system. The user interface design provides the look and feel of the system to the user, and the schema specification provides the details of the data behind the class and objects in the system.

Mr. Thomas Laliberty attended the joint meeting of the International Standards Organization (ISO) and the IGES/PDES Organization (IPO) in Dallas, TX on October 15-22 1992. Tom presented an overview of the MO program and a walk-through of the PCB EXPRESS information models developed under the MO program. Mr. Laliberty also attended an EXPRESS users group meeting held in conjunction with the ISO/IPO meeting. A copy of the presentation is included in Appendix I of this report.

Mr. Robert Bryant, Program Manager, attended the DARPA sponsored ASEM Conference on October 28-30, 1992 in Arlington, VA. Robert gave a presentation on the Manufacturing Optimization program. A copy of the presentation is included in Appendix II of this report.

Raytheon will begin the implementation of MO during the next quarter based on the software design specification for the Manufacturing Optimization (MO) System completed during the reporting period.

6. References

1. BR-20558-1, 14 June 1991, DARPA Initiative In Concurrent Engineering (DICE) Manufacturing Optimization - Volume I - Technical.

2. CDRL No. 0002AC-1, March 1992, Operational Concept Document For The Manufacturing Optimization (MO) System, Contract No. MDA972-92-C-0020.

3. CDRL No. 0002AC-2, March 1992, Description of CE Technology For The Manufacturing Optimization (MO) System, Contract No. MDA972-92-C-0020.

4. CDRL No. 0002AC-3, May 1992, Functional Requirements and Measure of Performance For The Manufacturing Optimization (MO) System, Contract No. MDA972-92-C-0020.

5. CDRL No. 0002AC-4, December 1992, Software Design Specification For The Manufacturing Optimization (MO) System, Contract No. MDA972-92-C-0020.

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10. ProductTrack Requirement Manager User Guide and Reference, Release 1.02 for Sun SPARC and Oracle RDBMS, Cimflex Teknowledge Corporation, October 1992.

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13. STEP Programmer's Toolkit Tutorial Manual, STEP Tools Inc., 1992.

14. STEP Utilities Reference Manual, STEP Tools Inc., 1992.

15. User Manual for the Project Coordination Board (PCB) of DICE (DARPA Initiative in Concurrent Engineering, July 10, 1992.

7. Notes

7.1 Acronyms

ASEM	Application Specific Electronic Module
CAEO	Computer Aided Engineering Operations
CDRL	Contract Data Requirements List
CERC	Concurrent Engineering Research Center
CM	Communications Manager
DARPA	Defense Advanced Research Projects Agency
DBMS	Database Management System
DFMA	Design for Manufacturing and Assembly
DICE	DARPA Initiative In Concurrent Engineering
IPO	IGES / PDES Organization
ISO	International Standards Organization
MEL	Mechanical Engineering Laboratory
MO	Manufacturing Optimization
MSD	Missile Systems Division
MSL	Missile Systems Laboratories
OOD	Object Oriented Design
OSF	Open Software Foundation
PCB	Project Coordination Board
PWA	Printed Wiring Assembly
PWB	Printed Wiring Board
PWF	Printed Wiring Fabrication
RAPIDS	Raytheon Automated Placement and Interconnect Design System
RM	Requirements Manager
ROSE	Rensselaer Object System For Engineering
SDAI	STEP Data Access Interface
STEP	Standard for Exchange of Product Model Data

Appendix I - IPO/ISO Presentation

Manufacturing Optimization

Supporting Concurrent Engineering and Information Exchange using STEP

ISO/IPO Quarterly Meeting
October 22, 1992
Dallas, Texas

Thomas Laliberty
Missile Systems Laboratories
Raytheon Company
Phone : 508-858-5756
Email : laliberty@as3.msd.ray.com

Sponsored by:
Defense Advanced Research Projects Agency
Defense Sciences Office
DARPA Initiative in Concurrent Engineering
ARPA Order No. [illegible]
Issued by DARPA/CMO under contract #MDA972-92-C0020

Manufacturing Optimization Summary

- **Project History**
- **Manufacturing Optimization Goals and Concepts**
- **MO Prototype**
  - Raytheon Automated Placement and Interconnect Design System (RAPIDS)
  - Manufacturing Optimization Support System (MOSS)
  - STEP Tools
  - CERC Tools
  - MO Prototype Architecture
- **Future Plans**
- **Express Models**

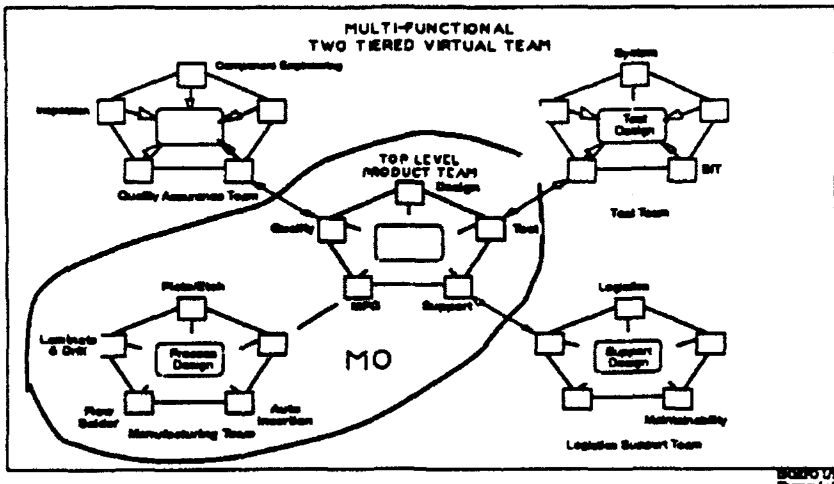
History

- **Raytheon awarded DICE Phase IV contract for MO**
  - DICE required user hardening of CERC tools
  - MO information modeling requirements
  - MO information sharing requirements
  - ROSE, STEP Tools Inc.
- **Project Based on Existing Raytheon Tools**
  - RAPIDS
  - MOSS
- **Masters Project at Rensselaer Polytechnic Institute**
  - EXPRESS modeling of PWB product data
  - Interface Raytheon PWB database with ROSE (bi-directional)

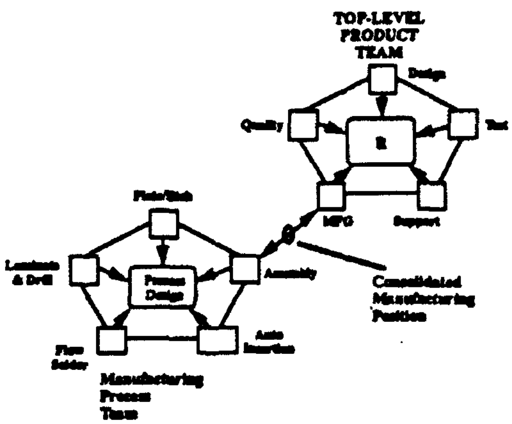
Manufacturing Optimization

- **DICE CE model replicates Human Tiger Team**
- **Unified Product Model accessible by computer networks**
- **Specialists work concurrently and share development ideas**
- **Growing complexity of products**
- **One specialist unable to adequately support position**
- **MO utilizes a refined CE model**
  - Two level approach
  - Top level product team
  - Specialized process virtual teams

Two Tiered CE VIRTUAL TEAM



Manufacturing Process Team



RAPIDS Overview

- **Raytheon Automated Placement and Interconnect Design System**
  - Concept to Design Tool
  - Up front analysis to identify problem areas
  - Put analysis tools in the hands of the EE
  - Experts help develop tools and then validate design
- **Concurrent Engineering Workstation for PWB design**
  - Interfaces to CAE Systems
    - Mentor
    - FutureNet
  - Placement Tool
    - Manual
    - Automatic
    - Fitting Analysis

RAPIDS Overview (cont')

- **CE Workstation for PWB Design (continued)**
  - Analyses
    - Connection Density
    - Routing Layer Estimate
    - Thermal
    - Reliability
    - Manufacturing (Predecessor to MO)
    - Layout Effects
  - Interfaced to PWB Routers
    - Racal-Redac
    - SciCards
    - CARI
    - Wire Wrap

MOSS Overview

- **Manufacturing Optimization Support System**
- **Provides Cost and Yield Estimates for Printed Wiring Boards (including ceramic substrates)**
  - bare board fabrication
  - board assembly
  - per operation
- **Based on Historical Model of Manufacturing Facilities**
- **Validates Design against Raytheon Design Guidelines**
- **Provides Design Guidance**
- **MOSS system for Mechanical also exists**

Tools Utilization

STEP Tools Inc.

- EXPRESS to C++ Compiler
- STEP Part 21 Input/Output Library
- STEP Object Management Class Library (ROSE)
- STEP design compare utility
- STEP design merge utility

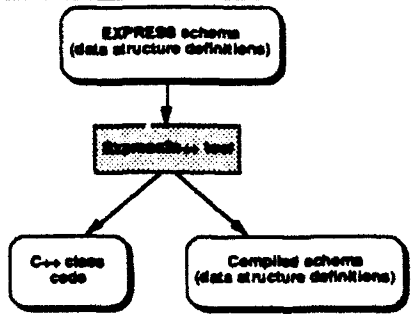
Raytheon Computer Aided Engineering Operations

- RAPIDS to STEP
- STEP to RAPIDS
- Difference Report Generator

Concurrent Engineering Research Center

- Project Coordination Board (PCB)
- Requirements Manager (RM)

STEP Tools Inc. Express Compiler



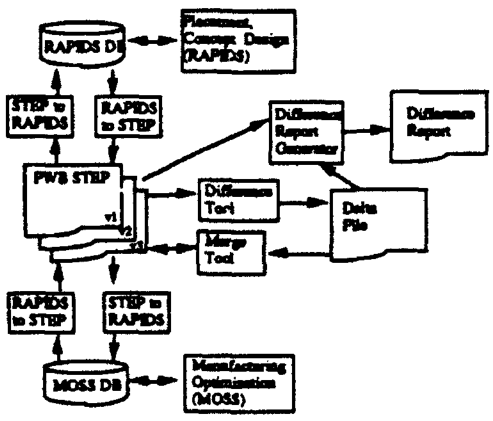
Step 1: Model data using the EXPRESS information modeling language.

Step 2: Generate C++ classes for each entity in the EXPRESS schema using the express2c++ tool. These classes will be subclasses of ROSE++ classes.

Step 3: Create instances of the generated C++ classes within a ROSE application. These are the STEP objects which will store your data.

Step 4: Write the step objects out to a STEP file.

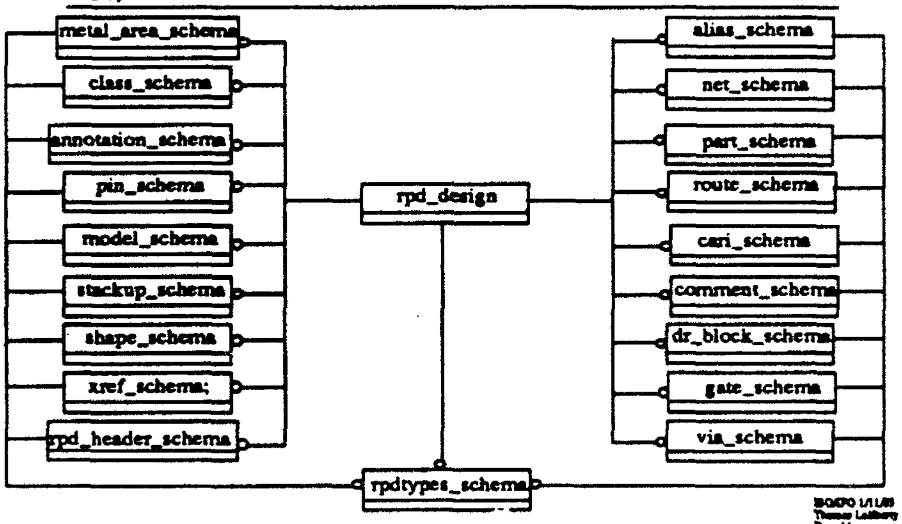
CE and Information Exchange Architecture



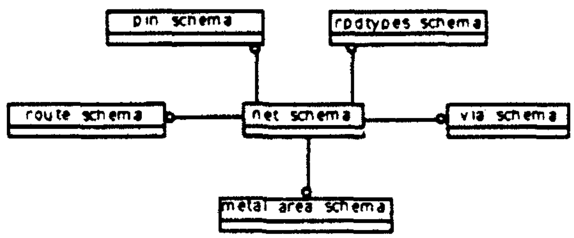
Future Plans

- **Utilize Part 210 once it becomes available for product data exchange**
- **Evaluate OODBMS for MO core module**
  - Concurrent access to data, transaction management
  - Object Store
  - Versant
- **Evaluate Configuration Control and Version Management Systems for STEP Data Entities if available**

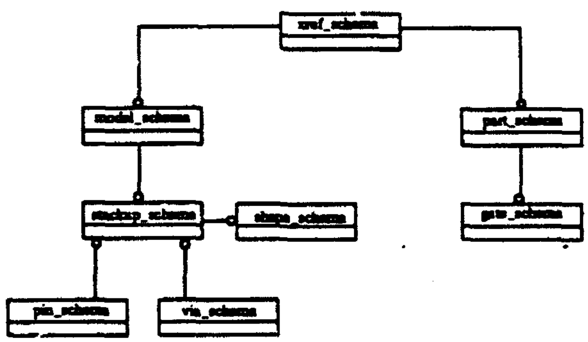
Schema Level Model



Net Schema



Library Related Schemas



Appendix II - ASEM Conference Presentation

Raytheon

DARPA

DARPA Initiative in Concurrent Engineering (DICE)
Manufacturing Optimization (MO)

Robert V.E. Bryant

DARPA ASEM Conference
Arlington, Virginia
October 28-30, 1992

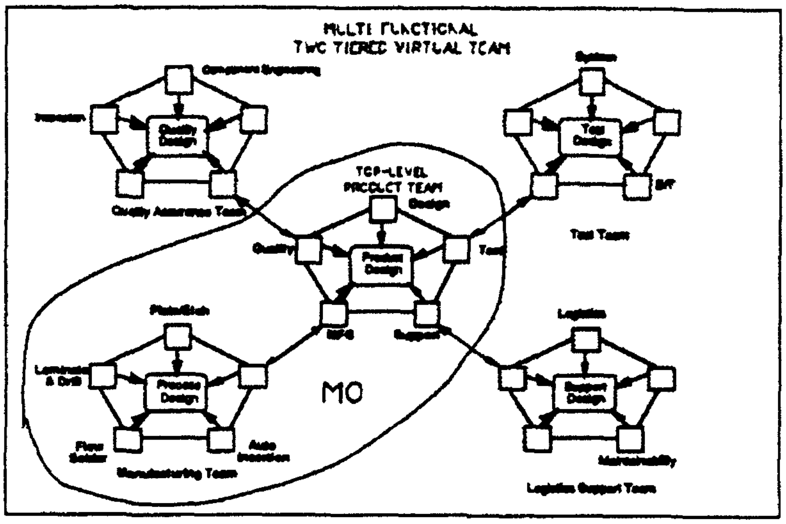
Raytheon *Manufacturing Optimization (MO)*

DARPA

MO Concept

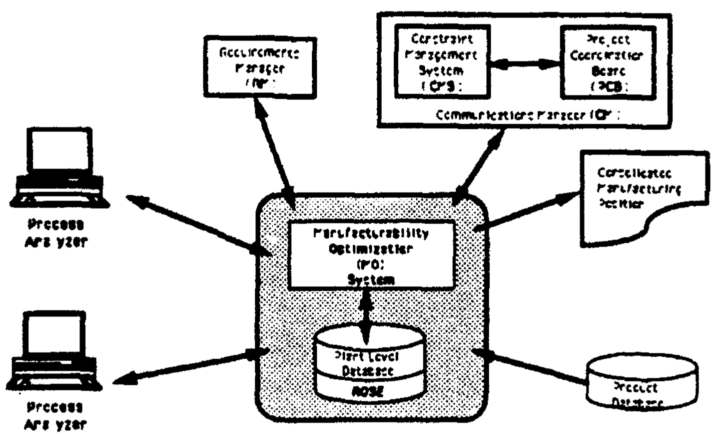
- Facilitate a two tier team approach to product/process development.
  - Product Design is analyzed by multiple manufacturing engineers
  - Product/Process changes are traded concurrently in the product and process domains
- Provide a tool set that supports DFMA
  - Process Selection Algorithm
  - Cost/Yield Estimates

Raytheon Manufacturing Optimization (MO)



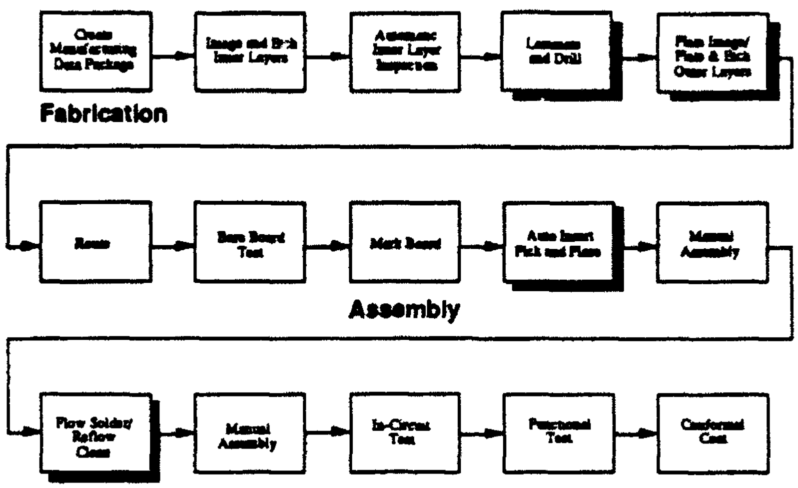
Raytheon Manufacturing Optimization (MO)

Proposed MO Architecture



Raytheon Manufacturing Optimization (MO) DARPA

Typical PCB Manufacturing Flow



Raytheon Manufacturing Optimization (MO) DARPA

Design Attributes That Influence Manufacturing Processes

LAMINATE AND DRILL PROCESS:

Laminate multiple circuit layers under heat and pressure and perform automatic precision drill.

CRITICAL DESIGN ATTRIBUTES:

Laminate
- Blind/Buried Vias
- Number of Layers
- Copper Balance
- Layer Stackup
- Board/Laminate Thickness
- Impedance Control Requirement
- Laminate/Prepreg Material
- Board Dimensions

Drill
- Number of Layers
- Pad Size/Accuracy
- Hole Size/Aspect Ratio
- Board Materials
- Board Thickness
- Unused Pad Removal
- Minimum Annular Ring
- Number of Holes, Sizes

Raytheon Manufacturing Optimization (MO) DARPA

<u>Design Attributes That Influence Manufacturing Processes</u>

IMAGE, PLATE AND ETCH OUTER LAYERS PROCESSES:
Photographic and chemical plating/etching operation.

CRITICAL DESIGN ATTRIBUTES:
- PTH Diameter/Aspect Ratio
- Available Registration Aids
- Feature Sizes, Spacing, Tolerance
- Material Selection
- Layer Stackup
  - Presence of Interconnect on Outer Layers
  - Position of Ground Planes
  - Metal Balance/Density
  - Outer Laminate Copper Thickness
- Length of Parallel Interconnect Lines

Raytheon Manufacturing Optimization (MO) DARPA

<u>Design Attributes That Influence Manufacturing Processes</u>

AUTO INSERTION/PICK AND PLACE PROCESS:
Automatic insertion of through hole components and attachment of surface mount devices.

CRITICAL DESIGN ATTRIBUTES:
- Insertability of each component type
- Number of components by insertion type
- Component orientation by component type
- Component-component spacing
- Component-obstruction spacing
- Board thickness vs. component lead length
- Lead diameter vs. hole diameter
- Static sensitivity of components
- Sequencer compatibility of components
- Component bonding/attachment method

Raytheon Manufacturing Optimization (MO) DARPA

Design Attributes That Influence Manufacturing Processes

FLOW SOLDER PROCESS:

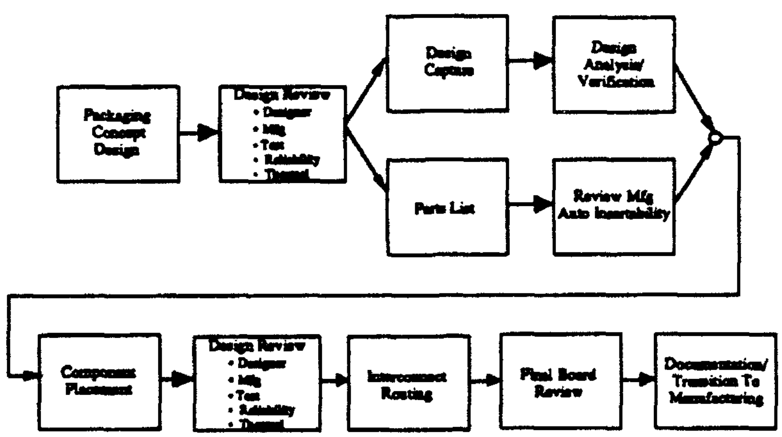
Through-hole components soldered using a "wave" of molten solder and surface mount reflowed using vapor phase, IR, convection, or combination.

CRITICAL DESIGN ATTRIBUTES:

- Board thickness/Lead protrusion
- Thermal sensitivity of components
- Metal Balance
- Component Orientation
- Board Geometry
- Presence of interconnect or ground plane on solder side
- Mixture of surface mount & through hole components
- Pad geometry, feature spacing, and orientation on solder side
- PTH lead diameter
- Aspect ratio of through-hole

Raytheon Manufacturing Optimization (MO) DARPA

PCB Design Flow



Raytheon Manufacturing Optimization (MO) DARPA

Packaging Concept Design

Function(s) Performed:
- Establish Design Concept
- Concept Review

Attributes Determined:
- Number of board types
- Board geometry (area, length, width, aspect ratio)
- Number of interconnect, power, and ground layers
- Layer stackup, layer-layer spacing, and tolerances
- PWB materials
- Design Rules: trace width, space, and via size
- Component family and attachment method
- Thermal management
- Test Strategy
- Cost, performance, and reliability budgets

Raytheon Manufacturing Optimization (MO) DARPA

Design Capture

Function(s) Performed:
- Define Design Details
- Capture Engineering Schematic
- Detail Design Review
  - Functional
  - Manufacturability Assessment
  - Thermal Analysis
  - Testability
  - Reliability
- Define/Review Engineering Parts List

Attributes Determined:
- Component Selection
- Schematic Capture
- Thermal, static, and noise sensitivity
- Component mounting/attachment method
- Circuit complexity and packaging density
- Operating frequency and clock rate

Raytheon Manufacturing Optimization (MO) DARPA

Design Analysis/Verification

Function(s) Performed:

- Perform Simulation
- Select Components
- Signal Analysis
- Load Analysis
- Write Detail Design Memo
- Write Preliminary Test Requirement

Attributes Determined:

- Timing and Fault Grading
- Critical Signals
- Preliminary Test Requirement Specification

Raytheon Manufacturing Optimization (MO) DARPA

Component Placement

Function(s) Performed:

- Process Schematic Database
- Define Component Distribution
- Define Power Dissipations
- Establish Placement Concept
- Perform Engineering Placement
- Review Placement

Attributes Determined:

- Component Location and Orientation
- Refine Design Rules

Manufacturing Optimization (MO) DARPA

Key Functions

- Two Tiered Virtual Tiger Team Communication
- Design System Interface
- Process Analyzer
- Guideline Analyzer
- Yield & Rework Analyzer
- Cost Estimator
- Manufacturing Advisor

Raytheon Manufacturing Optimization (MO) DARPA

Two Tiered Virtual Tiger Team Communication

- Product - to - Process Team Communication
  - Notification of design task completed or other pertinent status information.
  - Notification and issuance of database available for analysis.
  - Notification of alternative designs or trade-offs decisions under consideration.
- Process - to Product Team Communication
  - Notification and issuance of analysis results.
  - Notification and issuance of modified database with recommended changes.
  - Notification of changes to the process, guidelines, cost or yield models.

Raytheon Manufacturing Optimization (MO) DARPA

Design System Interface

- PWB product design data will be stored in ROSE
- RAPIDS will provide graphical CAD environment for displaying and manipulating PWB product design.
- MO will support an interface from RAPIDS to ROSE.
- RAPIDS to ROSE interface will be bi-directional to support manipulation of product data in ROSE and subsequent re-use in RAPIDS.

Raytheon Manufacturing Optimization (MO) DARPA

Process Analyzer

- Select the process sequence required to manufacture the product design based on product design or process parameters.
- Represents manufacturing process by three levels of abstraction: process, operation, and operational step.
- Process selection rules will be represented as "If - then" structures.

<u>Sample Fabrication Process Data</u>

Selection Rule: IF number of layers > 2 THEN

Opno	Op Description	LGrade	Setup	Run	Efficiency
10	"mark part no."	10	0.00000	0.12345	3.12345
20	"pierce tooling holes"	7	0.00000	0.12345	2.12345
30	"oxide treatment"	7	0.12345	0.12345	1.12345
40	"bake panels"	10	0.12345	0.23456	2.12345

Raytheon Manufacturing Optimization (MO) DARPA

Guideline Analyzer

- Evaluate a design against a set of design for manufacturing guidelines.
- Manufacturing guidelines will delineate quantitative and/or qualitative manufacturability issues.
- Guideline rules will be represented as "If - then" structures.

<u>Sample Guideline Data</u>

Guideline: IF power/ground layers are not symmetrically positioned in layer stackup THEN

Recommendation: In order to meet the bow and twist specification of less than 0.015 in/in, it is important to have a balanced construction. This means a board stackup should have nearly symmetrical positioning of power and ground planes and interconnect layers with respect to the center-line of the board cross section.

Raytheon Manufacturing Optimization (MO) DARPA

Yield & Rework Analyzer

- Calculates yield and rework rates for a selected process sequence associated with a product design.
- Yield and rework rates will be calculated on an operation level within the process sequence.
- Yield and Rework rate for each design feature associated with an operation will be calculated using a look-up table or through evaluation of an equation.

<u>Sample Fabrication Yield Look-Up Table Data</u>

Opno	Design Feature	Value	Scrap Rate
10	"aspect ratio"	5.0	0.05000
20	"aspect ratio"	4.0	0.02000

Raytheon Manufacturing Optimization (MO) DARPA

Cost Estimator

- Calculates recurring manufacturing cost for each operation of the process sequence. The following calculations will be performed:
  - Labor standard equations for setup and run time categories.
  - Estimated ideal cost for each operation based on labor standard values and wage rates.
  - Rework operation based on rework rate.
  - Estimated actual cost for each operation.
  - Total estimated ideal and actual cost for each process sequence.

Raytheon Manufacturing Optimization (MO) DARPA

Manufacturing Advisor

- Provides viewing of single process analysis results including process sequence, yield & rework, cost, and guidelines.
- Provides a mechanism for comparing and displaying the results from two runs of an analysis on a single process sequence.
- Provides the capability to summarize design features causing manufacturing guideline violations across multiple processes.
- Reports recommendations associated with guideline violations.
- Provides a summary report, identifying cost drivers, for each process contributing to a multi-process analysis for a given product design.

Raytheon Manufacturing Optimization (MO) DARPA

MO Prototype

Prototype Components:

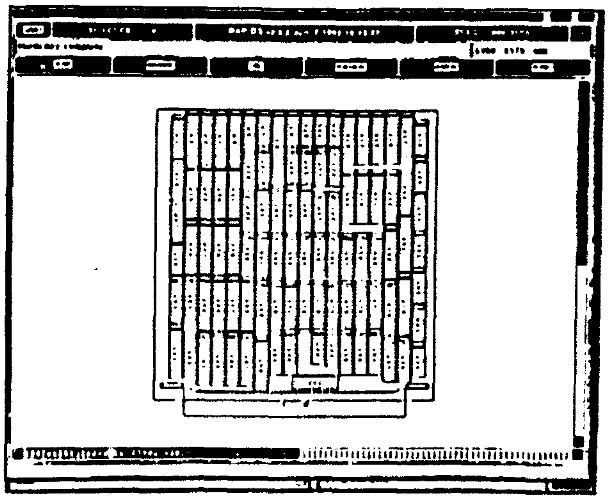
- RAPIDS and MOSS (existing Raytheon developed systems)
- Step Toolkit (including ROSE DB)
- Requirements Manager (RM) from Cimflex Teknowledge
- Project Coordination Board (PCB) from CERC

Demonstrates first pass at MO functionality for PWB including:

- Integration of concurrent design and analysis systems
- Support of two tiered product/process development
- Design conflict detection
- Design change merging

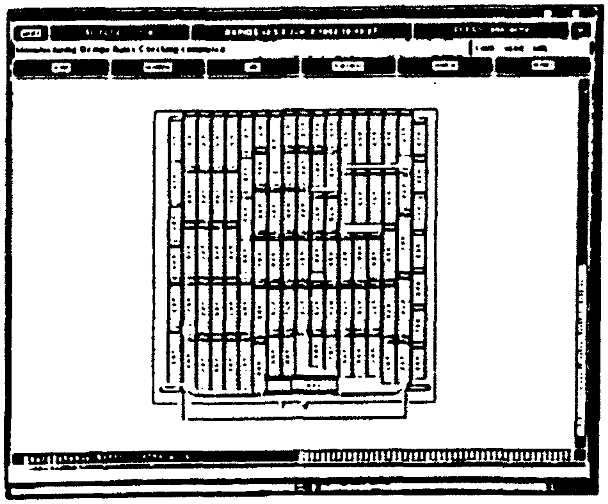
Raytheon Manufacturing Optimization (MO) DARPA

MO Prototype



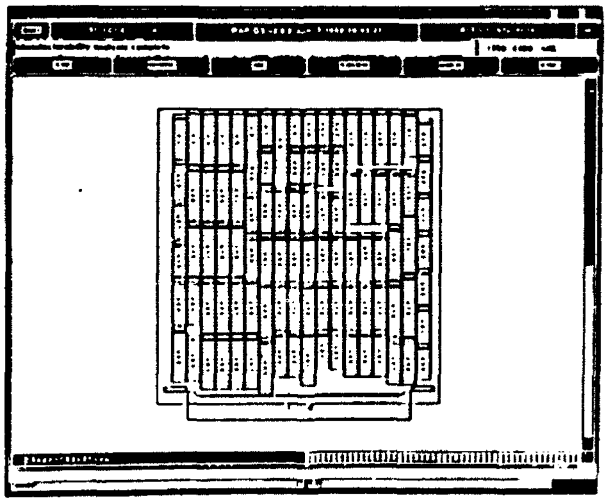
Raytheon Manufacturing Optimization (MO)

MO Prototype



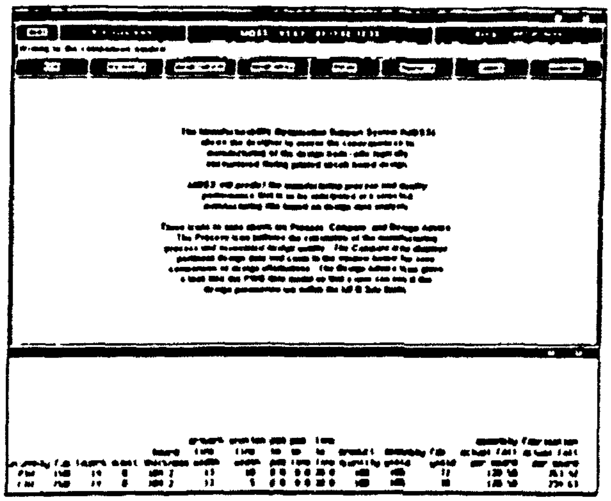
Raytheon Manufacturing Optimization (MO)

MO Prototype



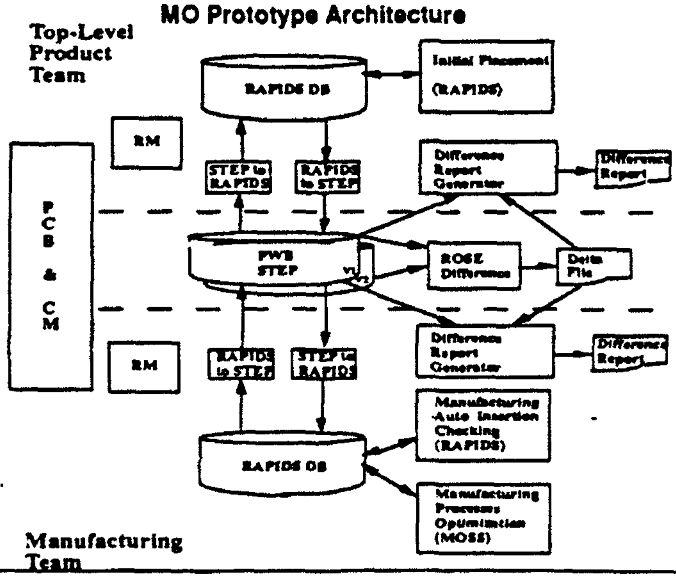
Raytheon Manufacturing Optimization (MO) DARPA

MO Prototype



Raytheon Manufacturing Optimization (MO) DARPA

MO Prototype Architecture



MO Process Modeling Technique

- Designed as AND/OR Dependency Graph made up of selectable manufacturing processes
- Selectable processes are either a Process, Operation, and Step Objects
- Each object in the process model can be connected to one or more objects at higher and/or lower levels in the dependency graph

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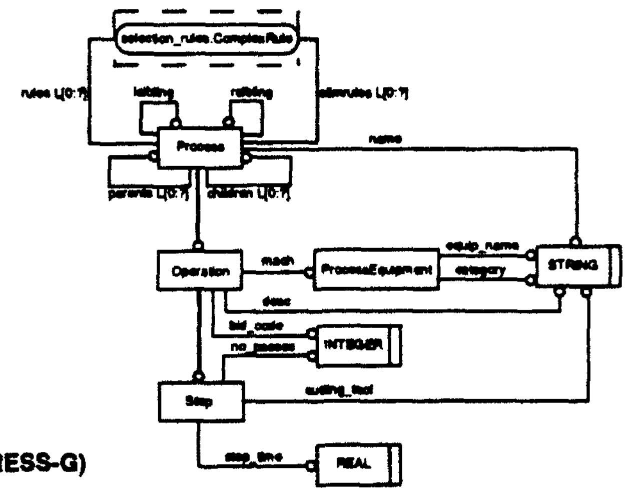
MO Process Model



(EXPRESS-G)

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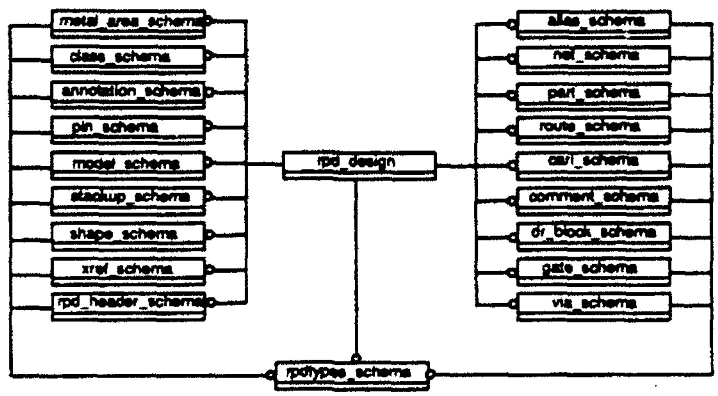
Schema Level Model



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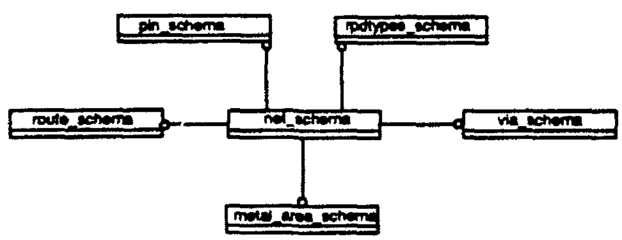
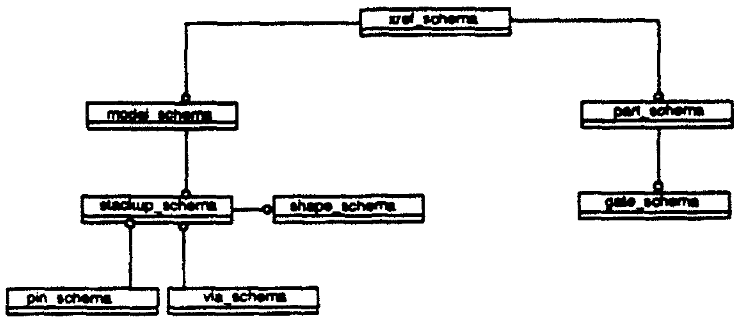
Net Schema



Library Related Schemas



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